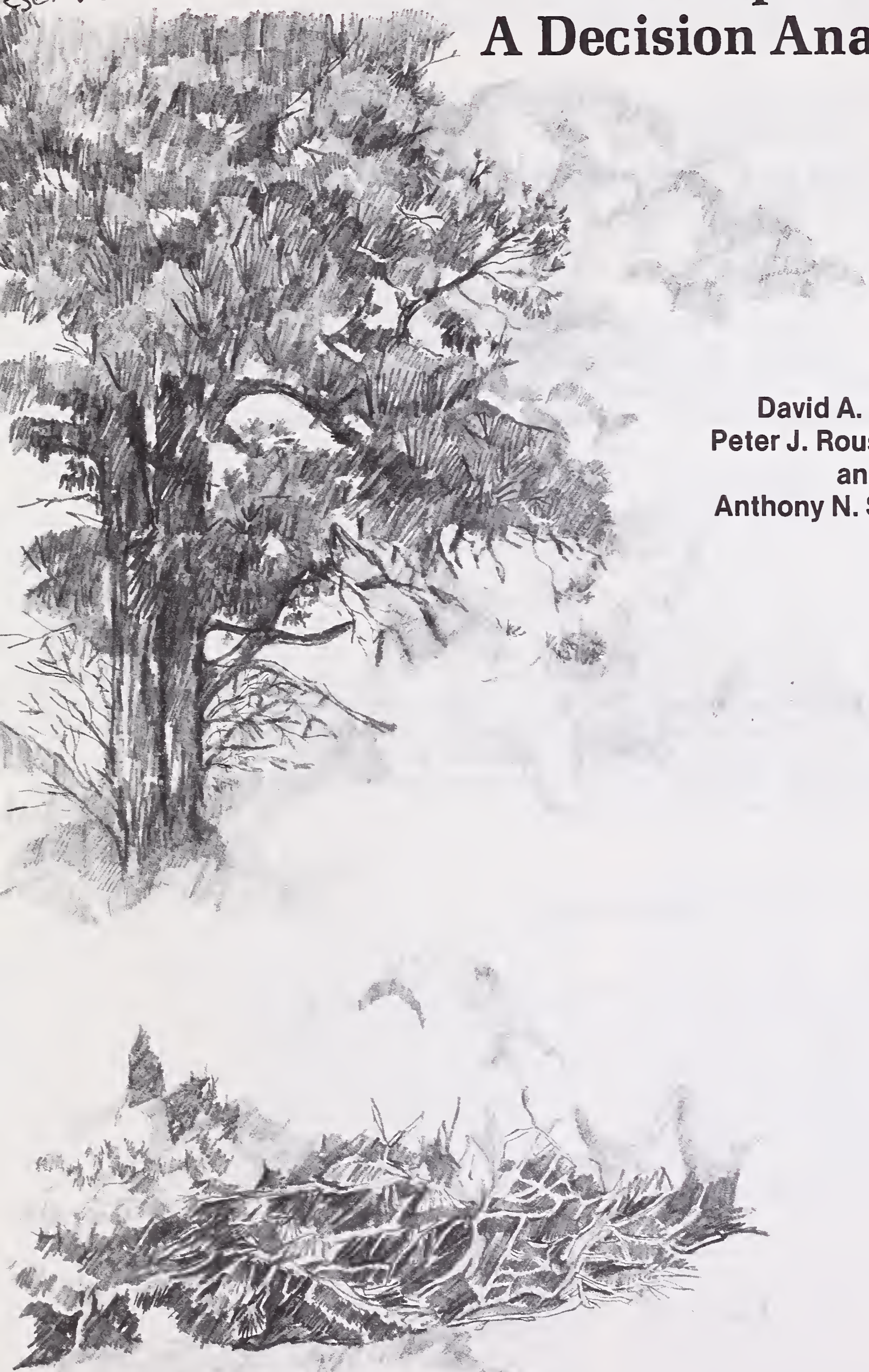
The Escaped Fire Situation: A Decision Analysis Approach



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Research Paper RM-244
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture

USDA Forest Service
Research Paper RM-244

February 1983

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Abstract

A preliminary decision analysis model addressing the choice among alternative suppression strategies on escaped wildfires is presented. A case study application of the model, in the context of an Escaped Fire Situation Analysis on the Wallowa-Whitman National Forest, is described and discussed.

Acknowledgments

The authors thank Al Oard, Forest Supervisor of the Wallowa-Whitman National Forest, for his cooperation, and the staff of the Wallowa-Whitman National Forest, particularly Dave Anderson, Gordon Foster, Dick Mangan, and Bruce McMillan, who provided much of the information used in the research and generally provided helpful suggestions and guidance in our effort. Assistance with the development and implementation of computer software was provided by Richard F. Yancik and James J. Allen; William G. Stillwell assisted with various analyses.

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The Escaped Fire Situation: A Decision Analysis Approach [1,2]

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Management Implications

Only about 5% of all wildland fires in the United States escape initial suppression efforts and become project fires, but these escaped fires account for roughly 95% of all wildfire-related costs and damages. As a result, Forest Service fire management policy calls for a careful analysis of all escaped wildfires in "real-time," to ensure that each fire is managed in the most efficient manner feasible.

Although the escaped fire policy has been in effect since 1978, current direction for the prescribed process is often too time-consuming and cumbersome for use in real-time emergency decisionmaking. Explicit means are not available for making tradeoffs among conflicting decision criteria, and there is no clear mechanism for crosswalking the analysis with broader resource management plans and programs. The result is that often one of the following two situations occurs: (1) The results of the hurried and incomplete analysis are rejected because they are counter-intuitive, thus wasting the time and effort devoted to the analysis; or (2) the analysis results are accepted and followed, but the necessarily incomplete nature of the analysis results in an inefficiently handled fire.

This report describes an initial study to determine the basic structure of escaped fire strategy decisions in terms of reasonable alternatives, appropriate decision criteria, and critical information uncertainties. It further investigates the use of concepts and methods of decision analysis to model these decisions and to identify crucial aspects of the decisions that need to be addressed explicitly, and aspects that are less crucial, where effort can be saved to improve analytical efficiency.

Results of this initial study suggest that decision analysis methods, together with concepts of multiattribute utility theory, can provide a consistent and logical framework within which to evaluate alternative suppression strategies on escaped wildfires. Additional research is needed, however, to explore possibilities for simplifying the model and reducing the number of value assessments required before the approach can be operationally useful in real-time.

Introduction

Current USDA Forest Service policy requires that suppression action on individual escaped wildfires be based on a formal analysis of alternative strategies—the Escaped Fire Situation Analysis (EFSA). Through the EFSA, a preferred suppression strategy is to be selected on the basis of expected costs plus net resource value changes (C + NVC), with additional consideration of social, environmental, and political factors. Thus, the EFSA decision is characterized by tradeoffs among the effects of fire on various resources as well as social, environmental, and political effects and fire suppression costs.

Because the EFSA decision is made after a fire has escaped initial attack efforts, it must be made rapidly, with little time for extensive analysis. It must also be made in the face of considerable uncertainty concerning important factors such as weather, fuels, topography, fire behavior, and the effectiveness of alternative suppression strategies. Information that is relevant to the decision comes from many sources: meteorologists, fire behavior officers, resource advisors, and fire suppression specialists. These considerations suggest that decision analysis (Brown et al. 1974, Howard 1968, Raiffa 1968) may be an appropriate aid for the EFSA.

Decision analysis has been applied to several other problems in wildland fire management. For example, Hirsch et al. (1979, 1981) applied decision analysis to guide the selection of an activity fuel treatment. Other studies have used decision analysis to determine the value of fire-related information in forest planning (Seaver et al.)[4] and the value of improved fuels and fire behavior information for fire budgeting and fuel treatment decisions (Barrager et al. 1982).

This paper describes an analytic approach that embraces the most important uncertainties associated with operational EFSA decisions. A retrospective application of the approach to an escaped fire situation on the Wallowa-Whitman National Forest is also presented and discussed. Although the specific decision analysis model used in this case study is far too complex and unwieldy for practical application, the aggregate results of several detailed case analyses, such as the one discussed here, should provide valuable insights on the desirable features of a workable, operational model. Some of the study's preliminary implications regarding prospects for operational use of decision analysis models in real-time decisions are discussed herein.

[4]Seaver, David A., Anthony N. S. Freeling, and Peter J. Roussopoulos. 1982. Value of fire-related information in forest planning. Decision Science Consortium, Inc., 7700 Leesburg Pike, Suite 421, Falls Church, Virginia. (In preparation).

Analytic Approach

Decision analysis, the basic analytical approach used in this study, allows the evaluation of decision alternatives by breaking a complex problem into clearly defined components: alternatives, uncertain conditions or events, and outcomes. Various methods are used to quantify the uncertainties, in terms of probabilities, and the possible outcomes, in terms of value or desirability. To evaluate each alternative, the values assigned to its possible outcomes are weighted by their respective probabilities of occurrence and summed to yield the expected overall value for the alternative. If the analysis has adequately captured the key elements of the problem, the preferred alternative is the one with the highest expected value (i.e., lowest C + NVC).

A relatively simple example will clarify the basics of this approach and introduce some of the elements of the EFSA problem. Actually the EFSA involves two separate decisions: (1) whether or not a new EFSA is needed for a new work shift; and, if so, (2) what fire suppression strategy should be adopted. This analysis focuses on the latter decision—strategy selection—but it can provide some informal guidance with respect to the new EFSA decision as well. Figure 1 shows a simplified decision tree that represents a hypothetical strategy-selection decision. The various components of this example are discussed below.

Alternatives

The decision tree in figure 1 represents a choice between two fire suppression alternatives: A and B. The square (decision) node at the left of the figure denotes this choice. The lines or branches emanating from this node denote the two alternatives being considered.

In practice, alternative strategies must be defined on a case-by-case basis by appropriate fire and resource management experts. Strategies are specified in terms of the forces to be used, the equipment and material to be used, and locations of firelines. They must also incorporate knowledge about the availability of resources and other fire suppression activities. Appropriate suppression strategies on escaped wildfires include various levels of confinement, containment, and control. They may range from the use of smokejumpers, retardant tankers, helicopters, tractors, pumpers, hand crews, and all other available resources to control the fire at the smallest possible size, to simply confining the fire within some large, predefined area, bounded by physical barriers to fire spread.

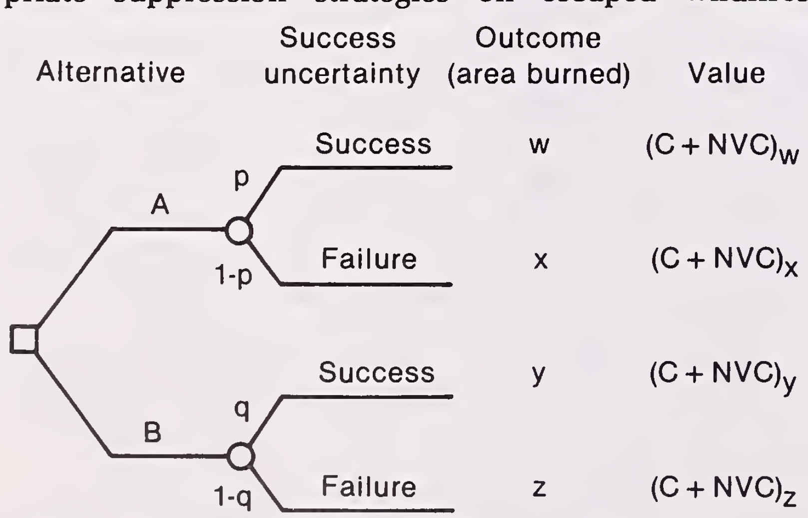


Figure 1.—Simple example of a decision tree for the Escaped Fire Situation Analysis.

Uncertainties

The outcome of any choice between the suppression alternatives will depend upon one or more uncertain events or conditions. In this illustrative case (fig. 1), a primary uncertainty, shown by standard convention with a circular node, is whether or not each of the alternatives (or either of them) will actually succeed in stopping the fire. The likelihood of the uncertain event (success) is quantified probabilistically using the best available information (the success probability is shown as p for alternative A and as q for alternative B). Such probabilities may be assessed using available data, expert judgment, or additional modeling. In the EFSA case study described subsequently, additional modeling was found useful in estimating the probability of success for each alternative.

Other uncertainties that influence the probability of success for a suppression alternative include production rates for assigned firefighting resources and fire behavior (rate of spread, intensity, occurrence of severe phenomena such as spotting and crowning, etc.). Furthermore, the probabilities of success for the alternative strategies may be differentially affected by these contributing uncertainties. For example, the success probability for a direct attack strategy may be reduced considerably more by more rapid fire spread than that for an indirect attack. Thus, the simple model in figure 1 could be expanded to include additional uncertain nodes that specify the probability of various fire behaviors, incorporating success probabilities that are conditional on fire behavior.

Fire behavior, in turn, depends on additional uncertain factors; specifically, weather (wind speed and direction, temperature, humidity, atmospheric stability, fuel moisture, etc.), topography, and fuel conditions. The model could be further expanded to explicitly include uncertain nodes and associated probability distributions to account for these variables, making fire behavior probabilities conditional on them. By cascading conditional relationships in this manner, it is often possible to separate highly difficult probability assessments into several component assessments that can be made by simple, straightforward means. As the number of required assessments increases, however, the task of the analyst grows commensurately.

Outcomes

Returning to figure 1, the outcome for each alternative (A and B) under each possible uncertain condition (success or failure) is expressed in terms of final

fire size. Values are then assigned to these outcomes indicating their desirability. These values (C+NVC) are measured as changes in management costs and resource values from conditions without fire. Costs include all expenditures associated with fire suppression activities. Resource value changes may be either positive or negative and may include effects—both of the fire and of suppression activities—on fisheries, wildlife, recreation, forage, timber, water (yield, storage, and quality), soils, air quality, visual quality, wilderness amenities, fuel hazards, improvements/structures, and public/social conditions (public concern, firefighter and public safety, cultural resources, private property, and employment).

In a highly explicit model, means for specifying and predicting fire effects and their associated values would likely involve consideration of several additional factors besides fire size, possibly including the nature and distribution of local vegetation, soil type, stage of phenological development, fuel and soil moisture conditions, behavior of the fire, mesoscale atmospheric conditions that affect smoke dispersal, and the prevailing social and political climate. A great wealth of literature deals with the physical and biological effects of fires vis-a-vis the production of various resource benefits, and much of it has been summarized and synthesized in a number of state-of-knowledge reviews (Lotan et al. 1981, Lyon et al. 1978, Martin et al. 1979, Sandberg et al. 1979, Tiedemann et al. 1979, Wells et al. 1979, Wright 1978). Despite the scientific interest in this topic, however, many important questions remain unanswered, and conflicts in existing evidence suggest that the needed answers will not be easily obtained. Many EFSA decisions, therefore, would likely require implicit consideration of most of these factors, incorporating judgmental assessments of physical, biological, social, and political effects where sound scientific data are unavailable.

Means for valuating the predicted effects of wildfires and associated suppression activities are, in general, not well developed either. Expected suppression costs for any chosen alternative can be established with a relatively high degree of reliability, but resource value change estimates are not as easily derived. Resource components that characteristically have no established market (e.g., wildlife habitat, visual amenities, and recreation opportunities) pose a significant source of uncertainty for fire valuation efforts.

Although a large share of the published fire valuation work has dealt strictly with marketable resources (Gorte and Gorte 1979), several comprehensive procedures have been proposed for valuating all wildland fire effects (Bakker 1975; Crosby 1977; Marty and Barney 1981; U.S. Department of Agriculture, Forest Service 1980a, 1980b). The fact that these procedures involve considerable detail and numerous manual tabulations suggests that some modifications would be necessary before they could be useful for EFSA decisions.

Perhaps the most promising of the above approaches is the Forest Service Fire Management Analysis and Planning procedure for fire valuation (U.S. Department of Agriculture, Forest Service 1980b). It is not less complex than the others, but presumably, for Forest Service units, it will have been completed in the development of the forest plan. Thus, fire damage and benefit estimates, on a per-burned-acre basis, will be available for each resource category by locally recognized fire size and behavior classes.

Alternatively, all effects and values could be assessed directly by judgmental means. Even if nonjudgmental methods are used where possible, some effects and values will necessarily remain judgmental (e.g., safety and visual quality). This topic is developed more fully in the Discussion section.

Analysis

Once the possible outcomes have been evaluated and specified in terms of effects and values, they are aggregated into a single index, C+NVC. Assuming C+NVC has been expressed on a per-acre basis, these index values are multiplied by the number of acres burned to produce a total C+NVC estimate for each possible outcome. Finally, the *expected* value of each alternative is calculated by multiplying the total C+NVC for each outcome by the occurrence probability of the outcome and summing these products over all outcomes. Using the example in figure 1 to illustrate this computation, the expected C+NVC for alternative A ($E_A\{C+NVC\}$) is:

$$E_A\{C+NVC\} = wp(C+NVC)_w + x(1-p)(C+NVC)_x \quad [1]$$

where p is the probability of success for alternative A, w is the area burned if A is successful, x is the area burned if A fails, and $(C+NVC)_w$ and $(C+NVC)_x$ are the net value changes (per unit area) for success and failure, respectively. Alternatives may then be compared directly on the basis of expected C+NVC.

Although the example offered in figure 1 is oversimplified, it serves to illustrate the general approach used to model the EFSA decision in this case study. Once represented by a decision analytic model, a specific EFSA decision can be analyzed in several ways. In addition to identifying the preferred suppression strategy given current information, value of information analyses (Howard 1966) can be conducted to guide information gathering or research activities to support the EFSA, and sensitivity analyses can be performed to determine the effects of model parameter variation. For example, varying weather conditions to see when a different strategy becomes preferred can provide guidance as to what weather changes may require a new EFSA. Some examples are described more completely for the case study application discussed below.

An Application

As an initial test of the use of decision analysis in the EFSA, a case-specific decision analytic model was tailored for a particular EFSA. The Wallowa-Whitman (W-W) National Forest in northeastern Oregon was

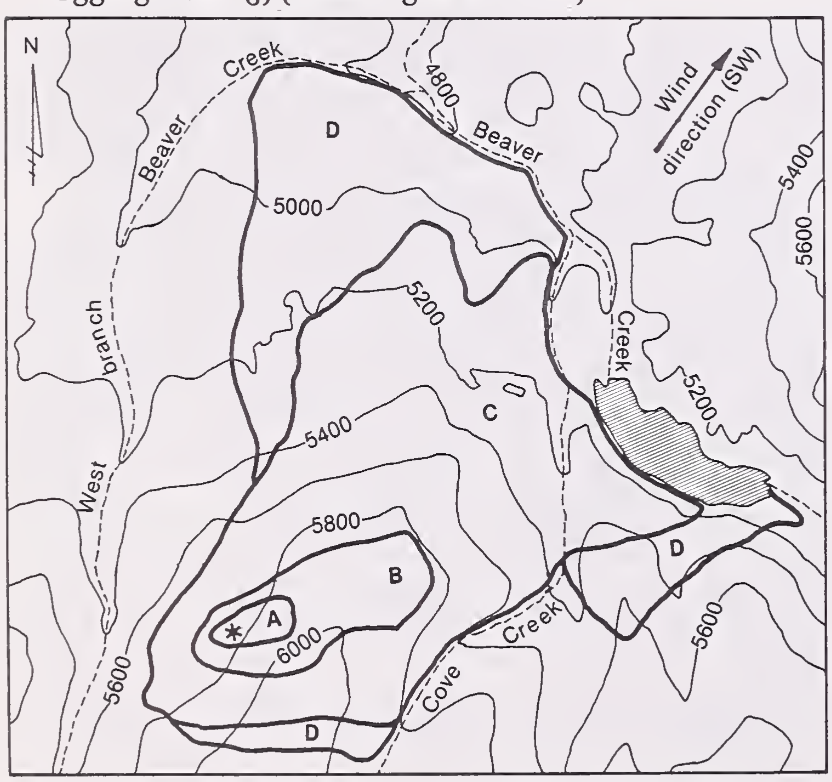
selected for the test application; the forest staff aided in the selection of an escaped fire situation that had been worked out previously as part of a training exercise—the Beaver Creek Fire. The salient conditions of the situation are as follows:

Location: The fire started at 2000 hr on August 11, 1980, at an elevation of 5780 feet within the La Grande City watershed (45°11′ N, 118°14′ W) (fig. 2). It was detected by aerial observer roughly 14 hours later— at 0955 hr on August 12.

Fire Behavior: At 1030 hr, when the EFSA is initiated, the fire is 2 acres in size, and is spreading to the northeast at 4-5 chains per hour. Flame lengths are estimated at 4-6 feet, corresponding to a fireline intensity of 100-300 Btu$\cdot$foot$^{-1}\cdot$second^{-1}. This intensity range is generally regarded as marginal for effective direct attack on the fire.

Weather: The wind is out of the southwest at 10-12 miles per hour. The temperature is 78° F, relative humidity is 34% and 10-hr timelag fuel moisture (Deeming et al. 1977) is 7%. The forest has been at the top of the "High" (3H) manning class for 14 days, and no change is forecast.

Fuels: The fire is burning in a large, continuous stand of lodgepole pine (*Pinus contorta* Dougl.), with moderate to heavy mortality and downfall due to a mountain pine beetle (*Dendroctonus ponderosae* Hopkins) infestation. Fuel models used for fire danger rating in the fire vicinity include: dense conifer with heavy detritus (G), short-needle conifer (H), and medium logging slash (J) (Deeming et al. 1977).



Scale: ½ mile

—5200— Topographic contour lines (200-foot interval)
-------- Rivers and streams
—— Proposed firelines
A Strategy identifier
* Point of fire origin
La Grande Reservoir

Figure 2.—Map of fire vicinity showing proposed fireline locations.

Alternative designation	Description	Estimated control time: Date	Estimated control time: Hour	Size if successful (acres)
A	—Stop fire at top of first ridge —Parallel attack —Use retardant and jumpers —Build hand line and burn out	8/12	2400	15
B	—Stop fire midslope before it drops into Cove Creek —Same tactics as A	8/12	2400	80
C	—Stop fire at Cove Creek —Indirect attack with hand tools —Use Cove Creek and road as line for backfiring	8/13	1000	600
D	—Stop at reservoir intake road —Anchor and backfire from road —Begin parallel line with tractor and pinch off	8/14	1000	1000

Figure 3.—Description of alternative suppression strategies.

Resources: Because of relatively small stem size, a depressed wood market, and heavy bark beetle mortality, the immediate fire area is characterized as low investment timber. Sustained spread to the northeast, however, will involve old-growth allocations of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). The fire is entirely within the La Grande City watershed, which produces some special concerns about siltation or other damage to the water system, and public interest is expected to be high.

Forest Service personnel identified four possible alternative strategies (fig. 3). Proposed fireline locations for the four strategies are shown in figure 2 above.

These alternatives were not necessarily mutually exclusive. In fact, they could be implemented sequentially, i.e., if A fails, try B, etc. In some such cases, however, the sequential strategy would produce higher costs and lower probability of success for the subsequent strategy.

An additional alternative (not shown in figures 2 and 3) was proposed to serve as an indication of the worst that could happen if no other strategies were successful. This alternative, E, called for stopping the fire at a distant, relatively bare ridge after the fire consumed about 10,000 acres. Throughout this analysis, it was assumed that the fire could be stopped there with probability one.

Figure 4 shows the basic decision tree for this problem. Initially, the choice (square node) is among the five alternatives. Then, whichever is chosen may succeed or fail with some probability (circular node). If it fails, any subsequent strategy can be selected; again, it may succeed or fail. This figure shows the expected C+NVC associated with each of the five alternatives. Alternative B is the preferred initial alternative identified by this decision analysis, primarily because of the relatively low probability of success for alternative A. These expectations were calculated using the probabilities of success shown at the chance (circular) nodes and the C+NVC values associated with each tip of the tree, which are also shown. The derivation of these quantities is discussed in the following sections. Uncertainties

regarding wind, fuel moisture, slope, fuel type, fireline intensity, spotting/crowning, and rate of spread have been incorporated either directly or indirectly (e.g., through use of manning classes to represent weather and fuel moisture) in the calculation of the probabilities at success nodes.

The analysis suggestion that B might be preferred to A (although they are relatively close in value) was contrary to the intuitive judgment of W-W staff. Several hypotheses regarding this difference are discussed following the description of the analysis, as are other results.

Probability of Success

Fuels were modeled by developing alternative scenarios composed of mixes of fuel types. The fuel types used were represented by National Fire Danger Rating System fuel models G, H, and J (Deeming et al. 1977). These scenarios, developed by W-W staff, are meant to be representative of possible fuel situations existing in the vicinity of the fire. Probabilities for the various scenarios were assessed by W-W staff. The scenarios and their assessed probabilities are shown in table 1. Because different alternatives include different areas, the fuel scenarios vary from alternative to alternative.

Rather than explicitly considering separate weather parameters in modeling the influence of possible weather scenarios on strategy success probabilities, fire weather conditions were represented by National Fire Danger Rating System manning classes, which integrate the various influential weather variables. The W-W National Forest uses six manning classes:

1 = Low
2 = Moderate
3L = Bottom of High
3H = Top of High
4 = Very High
5 = Extreme

They represent in ascending order more severe fire weather conditions. The manning class at the time of the fire was 3H and the fire danger forecast indicated it would remain 3H. Thus, uncertainty regarding weather was modeled by estimating a probability distribution over actual manning classes given the 3H forecast issued by the National Weather Service. That is, manning class probability estimates were made conditional on the National Weather Service fire danger forecast. This was accomplished by jointly examining the historical weather observation and forecast records of the nearest weather station (Furman and Brink 1975) with an adequate length of record (from the Johnson Rock Weather Station), for the period from July 15 to August 15, which was determined to be the most representative period. Separate estimates were required for the various fuel types because, for this study, manning classes were defined separately for the different fuel models. These conditional probability estimates are given in table 2.

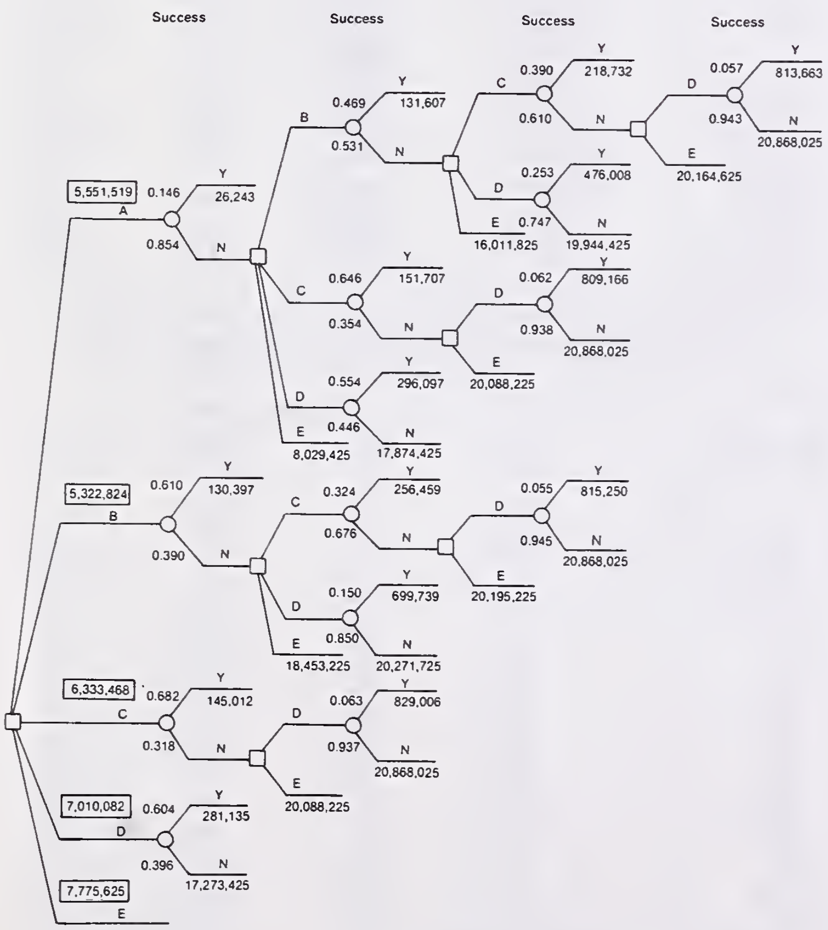


Figure 4.—Decision tree for Wallowa-Whitman National Forest Escaped Fire Situation Analysis. Enclosed numbers are the expected values (losses) of the five suppression alternatives, represented by A, B, C, D, and E. Success of the preceding strategy is represented by Y, and failure by N.

Table 1.—Fuel scenario definitions and probabilities

Alternative	Scenario	Probability	Fuel type percentage G	H	J
A	1	0.10	50	50	0
	2	.20	50	0	50
	3	.50	33	33	33
	4	.20	0	0	100
B	1	.40	0	80	20
	2	.60	10	70	20
C	1	.50	20	60	20
	2	.50	15	75	10
D	1	.40	20	50	30
	2	.60	10	65	25

Table 2.—Probabilities of manning classes, given the National Weather Service forecast

Actual manning class	Fuel type G	H	J
1	0.05	0.04	0.00
2	.07	.02	.08
3L	.29	.35	.32
3H	.50	.51	.43
4	.05	.04	.13
5	.04	.04	.04

Fire behavior was defined by three intensity (I) classes and three rate-of-spread (ROS) classes. Forest Service staff indicated that appropriate intensity classes would be

Class	Btu·foot^{-1}·second^{-1}
I_1 (low)	0-100
I_2 (medium)	100-700
I_3 (high)	>700

Rate-of-spread classes were

Class	Feet·minute^{-1}
ROS_1 (low)	0-10
ROS_2 (medium)	10-25
ROS_3 (high)	>25

Probabilities for these classes were also estimated using historical weather data for July 15 to August 15 from Johnson Rock Station. Data were processed for each of the fuel models, using the National Fire Danger Rating System (Deeming et al. 1977) fire behavior processor, which is built upon the Rothermel (1972) fire spread model. Intensity probabilities, shown in table 3, were conditional on manning class and fuel type, and ROS probabilities, table 4, were estimated conditional on fire intensity class and fuel type. Conditions required for spotting and/or crowning did not occur during the period of record examined, and W-W staff concurred that these severe fire behavior phenomona are rarely observed in areas similar to that being modeled.

Wallowa-Whitman National Forest fire management personnel provided assessments of the probability of success for each of the alternative strategies, given the various fire behavior characteristics. Only four behavior classes needed to be considered. The local experts indicated that if either ROS or intensity were in the high class, any alternative other than E would not be successful. In addition, several other combinations of intensity and ROS were not possible, given the probabilities in tables 3 and 4. Thus, the four types of fire behavior considered were

FB_1 .... Low intensity and low ROS
FB_2 .... Medium intensity and low ROS
FB_3 .... Medium intensity and medium ROS
FB_4 .... High intensity or high ROS

The assessed probabilities of success for possible strategy sequences, given the fire behavior class, are shown in table 5. Note that alternative E is always successful regardless of fire behavior and whether or not any other strategies have been attempted previously.

This information provides the basis for calculating the overall probability of success at any node in the decision tree (fig. 4). The derivation of these success probabilities is discussed in the appendix.

Costs and Value Changes

Suppression costs were estimated by W-W fire suppression specialists using standard Forest Service worksheets. These cost estimates are shown in table 6.

Table 3.—Fire intensity class probabilities, conditional on manning class and fuel type

Manning class	Fuel type	Fire intensity class I_1	I_2	I_3
1	G	1.00	0.00	0.00
	H	1.00	.00	.00
	J	0.61	.39	.00
2	G	.50	.50	.00
	H	1.00	.00	.00
	J	.00	.53	.47
3L	G	.00	1.00	.00
	H	1.00	.00	.00
	J	.00	.00	1.00
3H	G	.00	1.00	.00
	H	1.00	.00	.00
	J	.00	.00	1.00
4	G	.00	1.00	.00
	H	1.00	.00	.00
	J	.00	.00	1.00
5	G	.00	.83	.17
	H	1.00	.00	.00
	J	.00	.00	1.00

Table 4.—Rate-of-spread probabilities, conditional on fire intensity class and fuel type

Fire intensity class	Fuel type	Rate-of-spread class ROS_1	ROS_2	ROS_3
I_1	G	1.00	0.00	0.00
	H	1.00	.00	.00
	J	0.90	1.00	.00
I_2	G	.43	.57	.00
	H	1.00	.00	.00
	J	.39	.61	.00
I_3	G	.00	.00	1.00
	H	.50	.40	.10
	J	.01	.71	.28

Table 5.—Probabilities of success given fire behavior class and the sequence of strategies attempted

Alternative[1]	Fire behavior class FB_1	FB_2	FB_3	FB_4
A	0.60	0.00	0.00	0.00
AB	.65	.40	.00	.00
ABC	.80	.60	.18	.00
ABCD	.70	.55	.20	.00
ABD	.90	.65	.30	.00
AC	.90	.60	.20	.00
ACD	.70	.55	.20	.00
AD	.90	.65	.30	.00
B	.80	.50	.00	.00
BC	.80	.60	.18	.00
BCD	.70	.55	.20	.00
BD	.90	.65	.30	.00
C	.90	.60	.20	.00
CD	.70	.55	.20	.00
D	.90	.65	.30	.00

[1]*Probabilities are for the last alternative listed in the row. Other alternatives indicate those attempted previously. For example, ABC indicates that alternative A and B were attempted before attempting C, and the success probabilitities are for C, taking into account these previous attempts.*

The values, both resource and social, that W-W staff indicated could be changed as a result of the fire include the following:

- visual quality
- wildlife
- fish
- wood production
- recreation
- forage
- water quality
- water storage
- fuels
- public concern
- employment
- public safety
- firefighter safety

The amount of change depends on the size and intensity of the fire. W-W staff estimated the relative magnitude of the changes for each of the three fire intensity classes and each of the five possible fire sizes (determined by the five alternatives) on a per acre basis. These assessed changes are shown in table 7. Changes in all areas except public concern and firefighter safety were assessed as percentages of the status quo (no fire). (W-W staff felt most comfortable with the judgments when they were structured this way.) Public concern and firefighter safety were rated directly.

In order to calculate a single measure of NVC, relative values of changes in each category were needed. Thus, in addition to the estimates of the possible resource production changes, W-W staff provided assessments of the tradeoffs among various resource changes. This was accomplished by using a procedure advocated by Edwards (1977) based on an approximation of additive multiattribute utility measurement (Keeney and Raiffa 1976). In this procedure, the worst possible and the best possible changes in each resource category were first identified. These ranges are shown in table 8. Then W-W staff were asked to consider these ranges and rank the resource categories according to the relative worth of moving from the worst end to the best end of the range shown in table 8. Ratio judgments were then made of the relative values for categories having adjacent rank scores. For example, the relative value of the difference between a 10% (worst possible) and a 20% (best possible) improvement in forage production, the category ranked next-to-last, was judged to be 1.5 times as valuable as the difference between a 10% (worst possible) and a 20% (best possible) reduction in fuel hazard, the category ranked last (table 8). The next judgment was then that the possible range of changes in public concern was 1.1 times as valuable as that for forage production. After all such judgments were made, relative weights were derived for each category (e.g., the weight for public concern was $1.1 \times 1.5 = 1.65$) and normalized to sum to 1.0.

Firefighter safety was assigned the highest weight of all considerations (table 8), while, as might be expected for a municipal watershed, potential damage to the

Table 6.—Fire suppression costs (dollars) given fire behavior class and the sequence of strategies attempted

Alternative	Fire behavior class: FB_1	FB_2	FB_3
A	27,923	([1])	([1])
AB	140,192	358,324	([1])
ABC	294,275	294,275	606,247
ABCD	534,036	603,743	669,876
ABD	489,941	553,893	614,565
AC	291,361	291,361	600,245
ACD	534,036	603,743	669,876
AD	489,941	553,893	614,565
B	140,192	358,324	([1])
BC	294,275	294,275	606,247
BCD	534,036	603,743	669,876
BD	489,941	553,893	614,565
C	291,361	291,361	600,245
CD	534,036	603,743	669,876
D	489,941	553,893	614,565
E	2,430,225	2,430,225	2,430,225

[1]*Alternative would not be successful for this fire behavior.*

Table 7.—Fire effects on a per acre basis by fire intensity class and fire size[1]

Resource/ value	I_1 with Fire size (acres) of: 15	80	600	1,000	10,000	I_2 with Fire size (acres) of: 80	600	1,000	10,000	I_3 with Fire size (acres) of: 10,000
Firefighter safety	1	2	3	3	5	10	20	25	30	100
Water storage	−3	−3	−3	−3	−3	−10	−10	−10	−10	−25
Wood production	−5	−5	−5	−5	−5	+5	+5	−15	−15	−50
Recreation	0	0	+30	+30	+30	0	+30	+30	−10	−20
Visual quality	0	+10	+10	+10	+10	+10	+10	+10	+10	−15
Wildlife	+5	+5	+3	+3	0	+10	+5	+5	−5	−30
Fisheries	0	0	−10	−15	−25	0	−15	−20	−30	−35
Employment	0	0	0	0	0	0	0	0	0	+10
Public safety	0	0	0	0	0	0	0	0	0	−5
Water quantity	+5	+5	+5	+5	+5	+10	+10	+10	+10	+15
Public concern	0	15	60	65	100	15	60	65	100	500
Forage production	+20	+20	+20	+20	+20	+10	+10	+10	+10	+10
Fuels/hazard reduction	+30	+30	+20	+15	+10	+30	+10	+10	+10	+50

[1]*All effects are percentage changes from the status quo, except public concern and firefighter safety which are direct ratings. Note that a 15-acre fire would not occur with the middle fire intensity, and only a 10,000-acre fire would occur with the high intensity.*

Table 8.—Ranges and weights for value changes

Resource/value	Range Worst	Best	Rank	Normalized weight
Firefighter safety	100	1	1	0.186
Water storage	−25%	−3%	2	.168
Wood production	−50%	−5%	3	.142
Recreation	−20%	+30%	4	.103
Visual quality	−15%	+10%	5	.077
Wildlife	−30%	+10%	6	.071
Fisheries	−35%	0%	7	.065
Employment	0%	+10%	8	.062
Public safety	−5%	0%	9	.041
Water quantity	+5%	+15%	10	.032
Public concern	500	0	11	.021
Forage production	+10%	+20%	12	.019
Fuels/hazard reduction	+10%	+50%	13	.013
Sum				1.000

water storage system was considered the most important resource concern.

These weights were used to trade off all changes into a single measure of total change in utility. From an operational standpoint, it may not be desirable to aggregate all effects into a single measure of utility. Rather, it may be more appropriate to track various categories of effects as separate indexes, allowing the line officer the freedom to trade off these separate estimates in a nonexplicit fashion. In this analysis, however, we chose to represent the entire decision process as explicitly as possible; all effects were expressed in terms of a single utility index, C + NVC.

In this case, wood production was the common measure because a dollar value could be assigned; this then allowed the analysts to combine NVC with costs. The W-W staff estimated that the value of timber lost if all timber value were destroyed would be approximately $1,000/acre. By using this information and the ranges and weights in table 8, value changes in other resources can be traded off into dollars. For example, in considering effects on wildlife, from table 8

$$\frac{{}^{w}WL}{{}^{w}WP} = \frac{0.071}{0.142} = \frac{1}{2} \qquad [2]$$

where w is the weight assigned to the particular resource, and WL and WP are subscripts for wildlife and wood production, respectively. Since the value of a 100% loss of wood production is $1,000/acre, the value of the 45% difference between best and worst is $450/acre. (All values are assumed to be linear over the range in consideration.) The difference between worst and best for wildlife (a range of 40%) is then half this value or $225/acre, and the value of each percent change in wildlife is $225/acre ÷ 40% = $5.625/acre. The resulting overall NVC's per acre for the various alternatives and fire intensities are shown in table 9. The effect of varying the value of wood production is discussed in the following section.

Table 9.—Net value changes per acre (dollars) given final strategy and intensity class

Alternative	Intensity class I_1	I_2	I_3
A (15 acres)	+112	(1)	(1)
B (80 acres)	+192	−106	(1)
C (600 acres)	+295	−108	(1)
D (1,000 acres)	+262	−167	(1)
E (10,000 acres)	+165	−590	−2119

[1]*If attempted, this alternative would not be successful given the indicated fire behavior (see table 5).*

The expected total C + NVC for any fire shown in figure 4 was computed as

$$C + NVC = \sum_i P(FB_i)\,C_i + A\left(\sum_j P(I_j) NVC_j^A/ac\right) \qquad [3]$$

where $P(FB_i)$ = the probability of fire behavior class i (i = 1, ..., 4),
C_i = the cost of suppressing a fire of type i,
$P(I_j)$ = the probability of a fire with intensity j (j = 1, 2, 3),
NVC_j^A/ac = the net value change per acre produced by a fire of size A with intensity j, and
A = the number of acres burned.

Supplemental Analyses

Two types of analyses can provide relevant information in addition to that produced by the basic decision analysis. Sensitivity analyses can indicate the robustness of the results and which inputs produce any lack of robustness. Value of information analyses (Howard 1966) can guide the collection of additional information to reduce uncertainty in the decision situation.

In this analysis, it is quite apparent from the model (fig. 4) that varying cost and value parameters will not produce a significant change in the results (i.e., in the sense that a different alternative would be preferred). This can be seen by comparing alternatives A and B in the model. If alternative A fails, the subsequent structure of the problem is the same as if B had been the first strategy attempted, since if A fails, B has a lower expected C + NVC than C, D, or E. The C + NVCs in these two parts of the tree are quite similar, and any changes in cost and value parameters would have relatively little *differential* effect on expected C + NVC.

Nonetheless, the sensitivity of results to the dollar value of an acre of timber was examined explicitly. The results presented above used a nominal value of $1,000/acre. Also considered were values of $500/acre and $2,000/acre, which is equivalent to halving and doubling *all* resource values, and the basic results were found to be unchanged. At $500/acre, alternative A had an expected C + NVC of $3,157,801; B was still preferred with an expected C + NVC of $3,034,348; and C, D, and E were correspondingly higher. Similarly, with a value of $2,000/acre, the expected C + NVC of alternative A was $10,338,951 and of B, $9,899,778, while the others were again higher.

The best possible information, and therefore the information with maximum value, would be to know

which strategies would succeed and which would not. That is, the information would indicate one of five situations: (1) that A would succeed; (2) that A would not succeed and B would; (3) that A and B would not succeed and C would; (4) that A, B, and C would not succeed and D would; or (5) that no strategy except E would succeed. Contributing to the overall uncertainty in likelihood of success for each alternative, of course, are the individual uncertainties of weather, fuels, topography, fire behavior, and control effectiveness. The value of perfect information on which strategies would succeed and which would not provides an indication of the expected value of removing all uncertainty in these information components through research or additional information gathering.

In order to calculate the expected value of this information, we first must know the probability that each of the five possible situations will occur: $P(A)$, $P(\bar{A}B)$, $P(\bar{A}\bar{B}C)$, $P(\bar{A}\bar{B}\bar{C}D)$, and $P(\bar{A}\bar{B}\bar{C}\bar{D}E)$, where $P(\bar{A}B)$ denotes the probability that A fails and B succeeds. Each of these joint probabilities can be decomposed into conditional probabilities and $P(\bar{A}) = 1 - P(A)$, e.g.,

$$P(\bar{A}\bar{B}\bar{C}\bar{D}E) = P(E|\bar{D})P(\bar{D}|\bar{C})P(\bar{C}|\bar{B})P(\bar{B}|\bar{A})P(\bar{A}). \qquad [4]$$

The conditional probabilites were calculated in a manner similar to those at the nodes in figure 4, except in each case the probabilities of success given the fire behavior were those for the specified strategy when it was not preceded by any other strategy (i.e., table 5 line entries A, B, C, and D). These probabilitites were used because, of course, if the information indicates exactly which strategies succeed and which do not, none of the ones that do not would be attempted. For example, if the information were that A and B would not succeed but C would, then obviously A or B would not be attempted before C. Thus, since $P(\bar{A}\bar{B}C) = P(C|\bar{B})P(\bar{B}|\bar{A})P(\bar{A})$, it is calculated as follows from the information in tables 5 and A-1. $P(\bar{A}) = 1 - P(A)$, which is found by multiplying the entries for alternative A in table 5 by the corresponding entries for alternative A in appendix table A-1 and summing over the four fire behavior classes. Similarly, $P(\bar{B}|\bar{A}) = 1 - P(B|\bar{A})$, which is found using alternative B in table 5 and alternative AB in table A-1. $P(C|\bar{B})$ is calculated using alternative C in table 5 and alternative BC (fire behavior at C given B has failed) in table A-1.

The probabilities of these five situations are as follows:

$$P(A) = 0.146,$$
$$P(\bar{A}B) = 0.493,$$
$$P(\bar{A}\bar{B}C) = 0.128,$$
$$P(\bar{A}\bar{B}\bar{C}D) = 0.020, \text{ and}$$
$$P(\bar{A}\bar{B}\bar{C}\bar{D}E) = 0.213.$$

Given this information, the expected C + NVC is then calculated as before, using equation [3]. The probabilities of fire behavior and intensity classes are calculated as described in the appendix, and costs and NVC estimates come from tables 6 and 9, respectively. Note that costs are those for alternatives not preceded by attempting other alternatives, e.g., the costs for situation $(\bar{A}\bar{B}C)$ are those from the "C" row in table 6. Thus, costs (and C + NVC) are always less than or equal to those on the top branches of figure 4 where some costs are increased by previous attempts at other strategies.

For each of the five possible situations, the expected C + NVC's are $26,243, $131,607, $215,519, $760,269, and $20,868,025, respectively, producing an overall expected C + NVC of $4,556,395. The difference between this figure and the expected C + NVC of the optimal strategy (B) in figure 4, $5,322,824, yields the expected value of this information, $766,429. This value reduces to $432,773 if timber has a value of $500/acre, and increases to $1,433,744 with timber valued at $2,000/acre.

Discussion of Application

When W-W staff had previously evaluated this EFSA as a training exercise, they had determined that alternative A was the preferred strategy. Although the present analysis suggested that A was only slightly less attractive than B, it may be useful to consider why this result differed from the previous result. Three hypotheses are apparent. One results from a possible inadequacy in this analysis; another results from a possible bias in the current EFSA decisionmaking process; and a third could be produced by either an inadequate analysis or biased judgment.

This analysis did not take into account attitude toward risk. The implications of the values in figure 4 suggest that A might become preferred to B if risk attitude were considered. Intuition regarding this can be guided by considering the outcomes of selecting A or B. The choice is between the two gambles shown in figure 5, with outcomes being the expected C + NVC resulting from the values in figure 4. Although B has the better expected value, as risk aversion increases, preference will shift more toward A. Intuitively, this means the desire to avoid a loss increases more rapidly than the amount of the loss does. The choice of strategy A by the W-W staff may be a manifestation of risk aversion.

Alternatively, the model may adequately capture the relevant features of the decision problem. The W-W staff choice may result from an institutionalized bias toward keeping the burned area as small as possible,

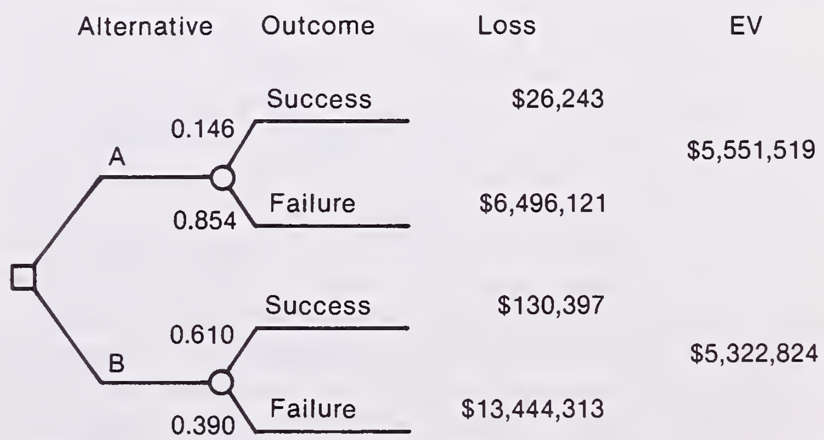


Figure 5.—Alternatives A and B as gambles.

i.e., toward stopping the fire at 15 acres (alternative A), if at all possible. Historically, this has been the Forest Service approach to fire suppression, and as such it may be ingrained in the thinking of fire management staff.

The third hypothesis is that the decision analysis generally gives a higher probability to fire behavior becoming more extreme than does the intuition of the forest staff members. The fire scenario as described included a statement that the manning class had been 3H for 14 days and no change was in sight. The decision analysis model, by incorporating historical probability distributions conditional on forecast weather, assigned probabilities of 0.08 to 0.17, depending on the fuel type, to higher manning classes actually occurring (table 3), while the forest staff may simply have assumed that the manning class forecast would be accurate. More severe conditions, of course, tend to support alternative B over alternative A.

Another point to be made regarding this application concerns the value of the best possible information. Such information would improve the expected value of the strategy decision by only about 14%. The reason for this is that the potential sequential nature of the strategies conforms rather closely to the optimal decision process given the perfect information. The reductions in the probabilities of success for a particular strategy caused by having taken some other strategy previously are rather small (nowhere more than 0.15), and the increase in costs is also small (always less than 10%). Perfect information would be of more value in a situation where alternatives could not be sequentially attempted, or where if they could be, it would be only with substantial changes in costs and/or probabilities of success. This does suggest, however, the value of identifying robust sequential strategies.

Discussion

Although the decision analytic model appears to have captured the basic features of the EFSA decision situation, a major problem that must be addressed before any implementation would occur is its size and complexity. No decisionmaker performing an EFSA would be interested in providing the assessments that were required for this model or in manipulating the model to ask "what if."

Two approaches to resolving this problem should be considered. The model can be simplified, for example, by using only the tree as shown in figure 4 without complex side models for determining the probabilities of success. These probabilities could be assessed directly at the time of use. A problem with this approach, however, would be the difficulty of Forest Service personnel accurately assessing these probabilities. These assessments would require consideration of complex factors, such as the relative likelihood of various fire behavior characteristics (and the variables that affect fire behavior) and how these likelihoods change as a result of attempting strategies. Comparison of probabilities assessed directly with those arrived at by modeling such as described here may provide useful insights on this question.

A second approach to solving the size and complexity problem is to provide most of the inputs to the model prior to use. Such inputs would essentially be default values that could be modified on-line if needed or desired. Development of the inputs would be done as a combination of research, training, and linking the decision analysis to existing data bases such as AFFIRMS (Administrative and Forest Fire Information Retrieval and Management System) (Helfman et al. 1975).

The approach to be taken in simplifying the model will depend to some extent on the degree to which the application described here is representative of most EFSA's. Specifically, it will depend upon whether, generally, strategies can be attempted sequentially, or whether, in many cases, alternatives are available that cannot be sequentially implemented. Much of the complexity of the model developed here is caused by the sequential nature of the strategies and the attendant effects on probability assessment. Additional EFSA decision situations must be examined to guide the design and development of a decision analytic approach to real strategy decisions on escaped wildfires.

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Appendix A

Derivation of Success Probabilities

At each node in figure 4, the probability of success, $P(S)$, is

$$P(S) = \sum_{i=1}^{4} P(S|FB_i)\, P(FB_i) \qquad [A1]$$

where FB_i $(i = 1,...,4)$ is the fire behavior class. $FB_1 = I_1 \cap ROS_1$, $FB_2 = I_2 \cap ROS_1$, $FB_3 = I_2 \cap ROS_2$, and $FB_4 = I_3 \cup ROS_3$, where I_1, I_2, and I_3 are low, medium, and high intensities, and ROS_1, ROS_2, and ROS_3 are low, medium, and high rates of spread. For an alternative where no other strategy has been attempted previously,

$$P(I_i \cap ROS_j) = \sum_k P(F_k) \sum_m \Big\{ w_m^{F_k} P(ROS_j|MOD_m, I_i) \times \sum_l [P(I_i|MC_l, MOD_m) \times P(MC_l|MOD_m)] \Big\} \qquad [A2]$$

where F_k = fuel scenario k,

$w_m^{F_k}$ = the proportion of fuel model *m* in scenario F_k,

MC_l = manning class *l*, and

MOD_m = fuel model *m*.

Also,

$$P(FB_4) = P(I_3 \cup ROS_3) = 1.0 - \sum_{n=1}^{3} P(FB_n).$$

Thus, the fire behavior probabilities vary across alternative strategies because the fuels differ among the strategies.

For alternatives where another strategy has been previously attempted, these probabilities are modified to reflect information gained as a result of knowing that a previously attempted strategy failed. For example, alternative A can succeed only if the fire has low intensity and low ROS. If we know A has failed, this suggests that the probability of a low intensity-low ROS fire is reduced. A heuristic model was developed to reflect this information:

$$P(FB_i|st_j) = \alpha_{i,j} \div \sum_{i=1}^{4} \alpha_{i,j} \qquad [A3]$$

where $\alpha_{i,j}$ is defined by the following recursive equation:

$$\alpha_{i,j} = P(FB_i|st_j^1) - [P(S_{st_{j-1}}|FB_i)\alpha_{i,(j-1)} + P(FB_i|st_{j-1}^1) - \alpha_{i,(j-1)}] \qquad [A4]$$

and

$$\alpha_{i,1} = P(FB_i|st_1^1)$$

and where st_j = the secondary strategy being considered,

st_j^1 = that strategy with no previous strategy attempted,

$P(S_{st_{j-1}})$ = the success probability of the previously attempted, unsuccessful strategy.

Any $\alpha_{i,j}$ with a computed value less than zero is set equal to zero.

Intuitively it is known that a certain proportion of the fires that fall into a particular fire behavior class could be successfully stopped by the previously attempted strategy. When the first strategy fails, the percentage of fires expected in this fire behavior class must be reduced by this proportion in considering the success probability for the next strategy. In effect, this is a filtering process, whereby fires with a given class of behavior are sequentially filtered out by potential successes with previous strategies.

The resulting probabilities for fire behavior classes with the various sequences of suppression strategies are given in table A-1. These probabilities and those shown in table 5 are combined using equation [A1] to produce the probabilities of success at the chance nodes in figure 4.

Table A-1.—Occurrence probabilities for the various fire behavior classes given the sequence of strategies attempted

Alternative	Fire behavior class FB_1	FB_2	FB_3	FB_4
A	0.243	0.131	0.176	0.450
AB	.701	.032	.042	.225
ABC	.342	.132	.207	.319
ABCD	.000	.036	.186	.778
ABD	.147	.106	.174	.573
AC	.638	.083	.110	.169
ACD	.000	.048	.178	.774
AD	.534	.069	.093	.304
B	.745	.027	.036	.192
BC	.241	.146	.241	.372
BCD	.000	.033	.186	.781
BD	.016	.116	.202	.666
C	.690	.071	.094	.145
CD	.000	.049	.179	.772
D	.602	.059	.079	.260

[1]*Probabilities are for the last alternative listed in the row. Other alternatives indicate those attempted previously. For example, ABC indicates that alternative A and B were attempted before attempting C, and the fire behavior probabilities are for C, taking into account these previous attempts.*

Seaver, David A., Peter J. Roussopoulos, and Anthony N. S. Freeling. 1983. The Escaped Fire Situation: A decision analysis approach. USDA Forest Service Research Paper RM-244, 12 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

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